THE EXPLORATION OF THE UPPER AIR BY MEANS OF KITES AND BALLOONS.

By WILLIAM R. BLAIR.

(*Read March 5, 1909.*)

Historical.

The kite, so far as we know, was first made and flown by the Chinese general, Han Sin, in the year 206 B. C. It was for a time used in war, being employed by the inhabitants of a besieged town to communicate with the outside, but later seemed to degenerate into a mere toy. Games in which kite strings are crossed and cut by the friction of one on the other are popular in China at the present time and great skill is shown in handling the small kites used for this purpose.

Professor William Wilson at Glasgow University and Benjamin Franklin at Philadelphia in the years 1749 and 1752 respectively were the first to use the kite in the study of upper air conditions. Wilson obtained temperatures at "great elevations" by means of self-registering thermometers, while Franklin used his kite as a collector of electricity.

Especial interest in upper air temperatures grew out of the consideration of the formula for refraction of light by the atmosphere, and kites carrying thermometers were again used in the years 1822 to 1827; this time by the Reverend George Fisher and Captain Sir William Edward Parry. At the same time upper and lower surface stations and captive balloons were first used for the purpose of obtaining temperatures aloft, the former by Sir Thomas Brisbane and the latter by the Earl of Minto. Readings were obtained at elevations of 400 feet with the kites and 1,340 feet with the captive balloons.

An editorial in the *Edinburgh Journal* for January, 1827, contains the following paragraph:

> To those meteorologists who have sufficient leisure and the means of performing such experiments, we would recommend the use of kites and balloons for ascertaining the temperature and state of the upper atmosphere. The Earl of Minto has obtained several very interesting results by the use of balloons.

Ten years later, Espey, in our own country, used kites to prove his theory concerning cloud altitudes. He held that the base of a forming summer cloud should be as many times 100 yards high as the temperature of the air at the earth's surface is above the dew point in degrees Fahrenheit, *i. e.,* that these clouds form in ascending currents and that the air cools one degree Fahrenheit for every 100 yards it ascends. He was able to put his kite in the base of a cloud 1,200 yards above the earth's surface and not only proved his theory within the error of observation, but found that the motion of the kite in the base of the cloud showed ascending air currents. He also obtained some striking electric effects, wire being used instead of string to fly the kite.

The report of the Franklin Kite Club, about 1838, on the discovery of ascending air currents gave further proof of Espey's theory and stated that this theory had the recommendation of the American Philosophical Society.

A contemporary of Espey, James Swain, flew kites for the purpose of determining daily the height of that layer of "electrified air whose positive electricity was concentrated enough to expand the leaves of an electrometer." Swain used No. 30 steel wire, which he wound on a reel four feet in circumference and having a glass axle like the one used by the Franklin Club of Philadelphia. Steel wire is now universally used in kite flying.

In 1847 Admiral Back flew kites from the deck of his ship, *The Terror,* and obtained free air temperatures over the ocean.

Up to this time the kites used have been small and rather unstable in their flight. Little more was done with them until Archibald, an Englishman, began to look into the mechanics of kite flight in 1883. In the meantime mountain stations and captive balloons were further developed in an effort to get temperature readings at greater altitudes than had thus far been possible. An observatory was established at Mt. Washington in 1870 and one at Pike's Peak in

1873. The results obtained by these observatories showed, as was pointed out by Professor Abbe and others, that the readings were not sufficiently isolated from terrestrial influences, and attention was again turned to kites.

Archibald showed the value of vertical planes for steering purposes, constructed kites of greater lifting power and in 1887 used them to carry up a camera. Captain Baden Powell in England, interested in the possible use of kites in war, made them large enough to lift a man. Eddy, at Bayonne, N. J., in 1890, constructed a diamond kite in which the ends of the cross stick were bent back, thus introducing a vertical component in the planes which added to their stability in flight. In 1893, Hargrave, an Australian, invented the box or cellular kite. This kite, although of more complicated construction than forms heretofore used, very soon displaced them for every purpose and seems to contain the fundamental principle upon which all stable aëroplanes are constructed.

Eddy's work was taken up by Mr. Rotch and his assistants at Blue Hill near Boston, and Hargrave's by the U. S. Weather Bureau under the immediate direction of Messrs. Marvin and Potter. Marvin's study of the mechanics and equilibrium of kites led him to make some modifications in the original box pattern. The Marvin-Hargrave kite, at present quite widely used, is not only more efficient, but is stronger and, for meteorological uses, more convenient in details of construction than the Hargrave. About this time Marvin designed a meteorograph and convenient hand reels for the wire which were used in a series of upper air observations made at seventeen different stations during the summer of 1898. In this series daily flights were attempted but only 44 per cent. of these attempts were successful, the failures being due to lack of wind or other adverse conditions. Of the 1,217 ascensions made, about 180 were a mile in height, while two were slightly over 8,000 feet. The observations made have been reduced and are published in Bulletin F of the U. S. Weather Bureau.

Nearly all first rate weather services now have one or more upper air observatories. Our own upper air work has been concentrated at Mt. Weather, Va., under the immediate direction of the writer, where, since the first of July, 1907, daily except Sunday, ascensions have been made with either kites or captive balloons, the latter being used only when the wind is insufficient to support the kites, or about one day in twenty. The apparatus in use at Mt. Weather is still undergoing improvement. The mean height at which daily (except Sunday) temperature and other observations are obtained is approximately 3,000 meters, or about 2 miles, above sea level. The highest altitude so far attained by means of kites is 7,044 meters, about 4⅜ miles. This flight was made at Mt. Weather on October 3, 1907. Flights closely approximating this in height were made at the same observatory on April 14 and September 30, 1908, while the fourth highest record, 6,430 meters, was made by the German Observatory at Lindenburg in November, 1905.

In the same year that Hargrave invented his kite, Charles Renard suggested the use by meteorolgists of small free balloons made of paper or other suitable material and having sufficient lifting power to carry up self-recording instruments. A balloon of this sort partially inflated with hydrogen at the earth's surface rises until the gas expands sufficiently to burst it, and the instrument is let down safely from this point by means of a small parachute.

Teisserenc de Bort, at his observatory at Trappes, Paris, and from the decks of ocean steamers, has obtained upper air records of great importance to meteorology with these paper balloons as well as with kites. More recently Assmann introduced india-rubber balloons about six feet in diameter. These are now the more generally used.

Preparatory to an ascension, this balloon is filled until the rubber begins to stretch, *i. e.,* from 3.5 to 4 cubic meters, depending on the weight it is to carry. The instrument is suspended from a small parachute thrown over the balloon, space being provided for the expansion of the latter to two or three times its diameter or to about twenty times the volume it had at the earth's surface. Sometimes two balloons are used, one of which bursts—the other lets the instrument down slowly. Records of temperature and humidity have been obtained at altitudes of 25,000 meters, over 15 miles above sea level with sounding balloons.

At present about twenty-five observatories—two in this continent, one in India, the others in Europe—are coöperating with the

International Commission for Scientific Aëronautics, using either kites or sounding balloons, or both. Captive and manned free balloons are occasionally used. Of these observatories, the universities of Manchester and Kasan each maintain one.

Apparatus and Methods.

The site chosen for an upper air observatory is to some extent determined by the kind of work to be done. A kite field should be clear of trees and other obstructions that might either entangle the wire or hinder the movements of the men who manipulate the kites. It should be situated on an eminence just high enough to prevent its being sheltered by any other in the immediate vicinity, but not high enough to introduce the complications of mountain and valley effects, unless indeed such local effects and not the general conditions obtaining in storms as they pass, be the object of the study. It is well if the country for thirty miles around in the vicinity of the field be free from large bodies of water and inhabited, for kites break away at times and these conditions facilitate their return. Close proximity to a city, on the other hand, is likely to bring kite flyers into unpleasant relationships with the local telephone and other electric companies who transmit power on overhead wires.

For captive balloons the conditions should be the same as for kites. Sounding balloons may be started from any place at which the true surface conditions can be recorded for comparison with the upper air data, except that the land area immediately to the east should be free from large lakes and fairly well settled. The balloons set free in this country by Professor Rotch have invariably traveled in an easterly direction and landed within a radius of 300 miles from their starting point. Each balloon carries with it instructions to its finder for packing and shipping and informs him that he will be rewarded for his trouble. This plan has brought back about 95 per cent. of all sounding balloons liberated in St. Louis, the only place in our country so far chosen for this work.

The ideal upper air observatory is one at which all three of these methods may be used, kites and captive balloons being less expensive and more efficient for levels up to 3,000 or 4,000 meters, 2 or 3 miles, and sounding balloons for higher levels.

The self-recording instruments used in kite and sounding balloon work are numerous in variety. Many observatories have instruments made from special designs. All are built on essentially the same plan. A clockwork rotates a cylinder which is covered with either a sheet of paper ruled to scale or a sheet of smoked paper or aluminium. Upon this sheet the pens or points, as the case may be, connected with their respective elements, trace the conditions. Paper scales are the more convenient and are used when the temperatures to be recorded are not so low as to freeze the ink. The instruments are made as light as possible, aluminium being the metal used in the construction wherever it can be adapted. From 750 to 1,500 grams is the usual weight of an instrument, those for use in kites being more substantially built than those for use in balloons. The anemometer usually consists of a small aluminium pin wheel mechanically geared to the pen—some are electrically connected. The hair hygrometer is the only form yet available for self-recording purposes that is light enough. The temperature is measured with either a bimetallic element or a partially coiled tube containing toluene. The barometer is of the aneroid type. The order of accuracy of these instruments is not high. Difficulty is experienced in keeping the anemometer properly oriented while the kite is flying. The hair hygrometer, if kept in good condition, probably records within less than 5 per cent. of the correct value. Records of pressure are, in nearly all cases, correct to within 2 mm., in many to within 1 mm. The temperature may be relied upon to one degree Centigrade in the records obtained from most kite flights, to less in many. When used in sounding balloons at very great altitudes the absolute error in any element is of course greater than those mentioned. In this case no anemometer is used, the wind velocity being determined from observations on the drifting balloon with one or more theodolites.

The differences in the various instruments consist chiefly in the way of exposing the elements so as to best obtain true records of the conditions in the vicinity of the instrument. It is essential that the temperature element especially be properly ventilated and insulated. The method of ventilation is of course different in sounding balloon and kite instruments. The former, being carried by the

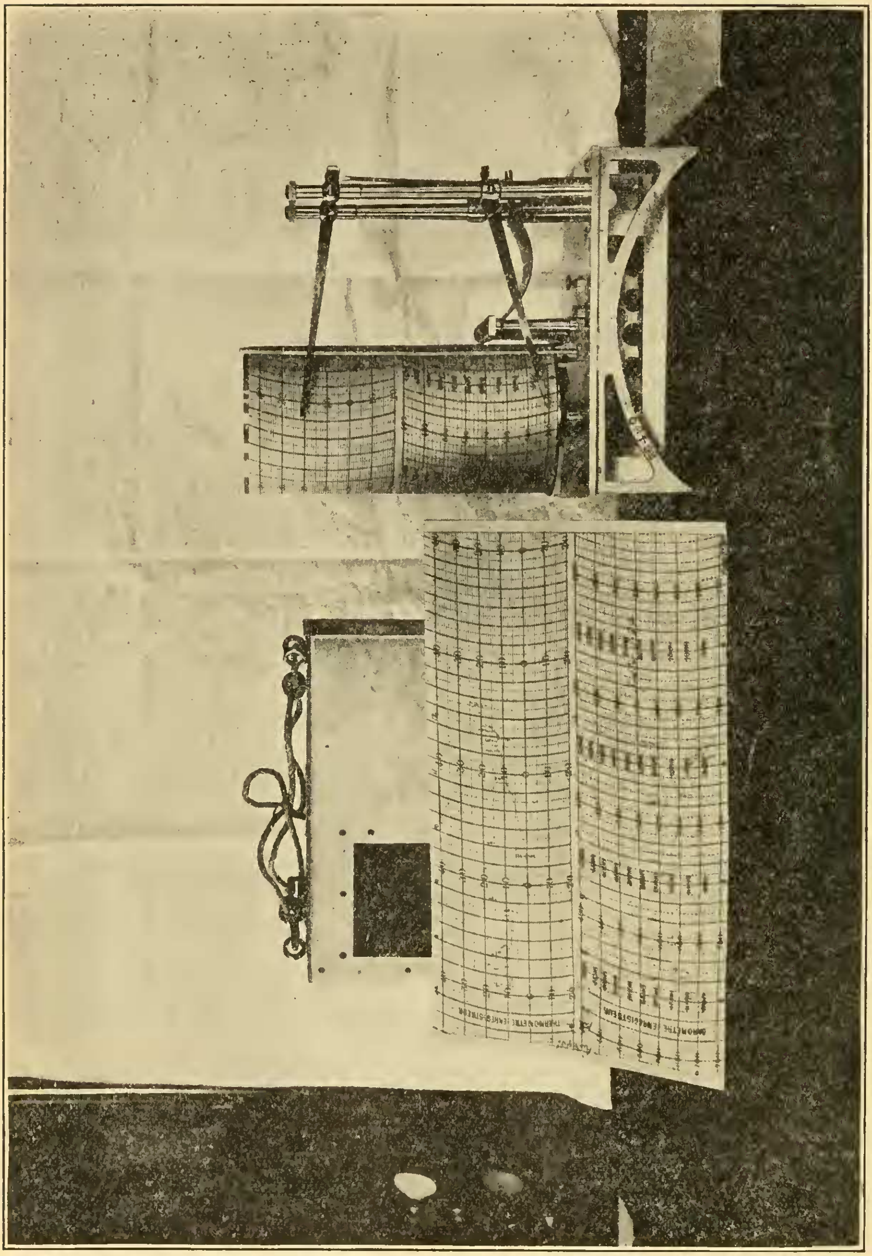


Fig. 1. Richard meteorograph.

wind, is in a calm except for its own upward motion through the air. It is therefore exposed in a vertical tube at the top of which is a funnel to insure the passage of a sufficient air current through the tube and about the element. The latter are held by the kites in the horizontal current in which the kite flies. The velocity of this current is always sufficient to keep the temperature element well ventilated so that care need be taken only to see that the element is in this current and screened from either the direct or reflected rays of the sun.

The meteorographs in use need comparison with standard instruments, at first to determine their scale values, frequently thereafter to guard against error due to slightly defective elements. Before and after an ascent the instrument is placed in a standard shelter with standardized instruments and allowed to record. Frequent readings of the latter are taken not only at these times but during the entire ascension. A base line for computation of altitudes is thus furnished, also a record of surface conditions for comparison with those of the upper air. To facilitate this computation and comparison, as well as to avoid errors due to the sluggishness of the elements, stops in the ascent and descent are made at frequent intervals. These stops need be for but a few minutes. Their times are recorded at the lower station and they are easily distinguishable on the traces. Of course it is impossible to make such stops with sounding balloons, and consequently instruments sent up by means of them should be, to some extent, at least, tested for sluggishness in addition to the tests made for scale values.

The cellular kite invented by Hargrave or some of its numerous modifications is the one most generally used for meteorological purposes. The Marvin-Hargrave kite, in which three planes are put in the front cell and the entire framework strengthened by fine steel wire braces, is the one in use at Mt. Weather. With slight modifications in the size and shape of the planes and in the proportion and distribution of lifting and steering surfaces, this kite has been made to serve in all winds from 3.5 to 22.5 meters per second. The dimensions of a medium-sized kite, one well adapted to carrying an instrument in winds of from 5 to 10 meters per second, are as follows:

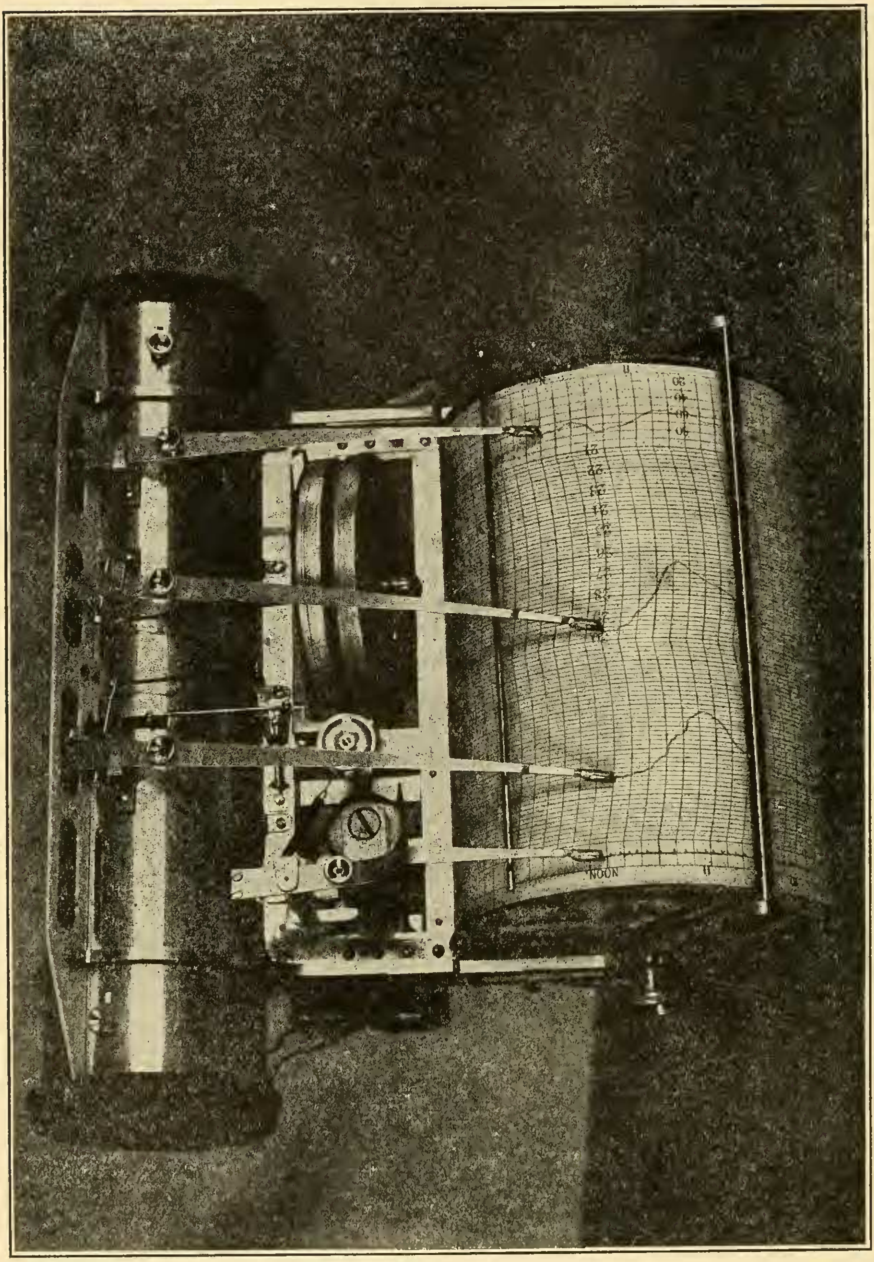


Fig. 2. Marvin meteorograph.

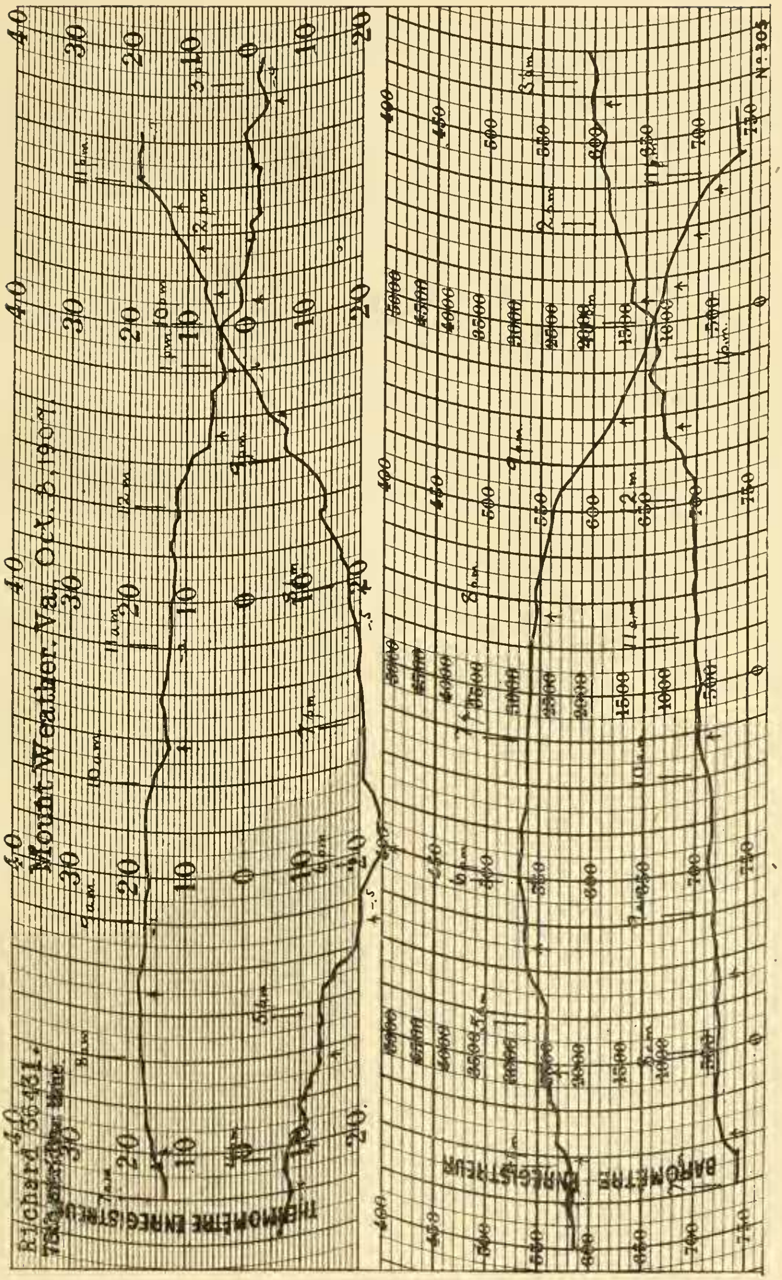


FIG. 3. Record from flight of October 3, 1907.

Height	204 cm.
Width	197 cm.
Depth	81 cm.
Width of planes	64 cm.
Plane space	76 cm.
Weight	3.2 to 3.8 kg.

There are five lifting planes, so called, and four steering. The area of the lifting planes is 6.3 square meters, while that of the steering planes is one third as much. Kites varying from these dimensions and necessarily therefore from these proportions are built for winds higher and lower than those to which the above-described kite is adapted. A type of kite which has flown in winds up to 22.5 meters per second has lifting planes aggregating 5.4 square meters in area. Its steering planes have half this area. It is a longer, narrower kite than the one whose dimensions are given above. A kite that has carried an instrument in winds as low as 3.5 meters per second has for the total area of its lifting planes 11.2 square meters.

The term lifting is not properly applied to any plane in the rear cell of a Hargrave kite, the function of that cell being more particularly steering. When a kite of the pattern described is sent up in a fog or low cloud in which the temperature is below freezing, ice crystals are found to attach themselves to the under side only of the three parallel planes in the front cell, but on both sides of all other planes in either cell, showing that practically all of the lifting is done by the front cell. A study of the formation of these crystals and the amount of ice deposited on different parts of a plane is very helpful in determining the most economic width and location of planes in a kite or other aëroplane.

At Mt. Weather we attach the meteorograph to the middle back rib of the first kite just behind the front cell. This insures it proper ventilation during the flight and adequate protection against injury in case the kite breaks away. Other, secondary, kites are attached to the line at intervals depending on the wind velocity and in numbers depending on the length of line put out. Their purpose is to support the wire. Twelve kites with a combined lifting plane area of 77.4 square meters is the greatest number we have ever used

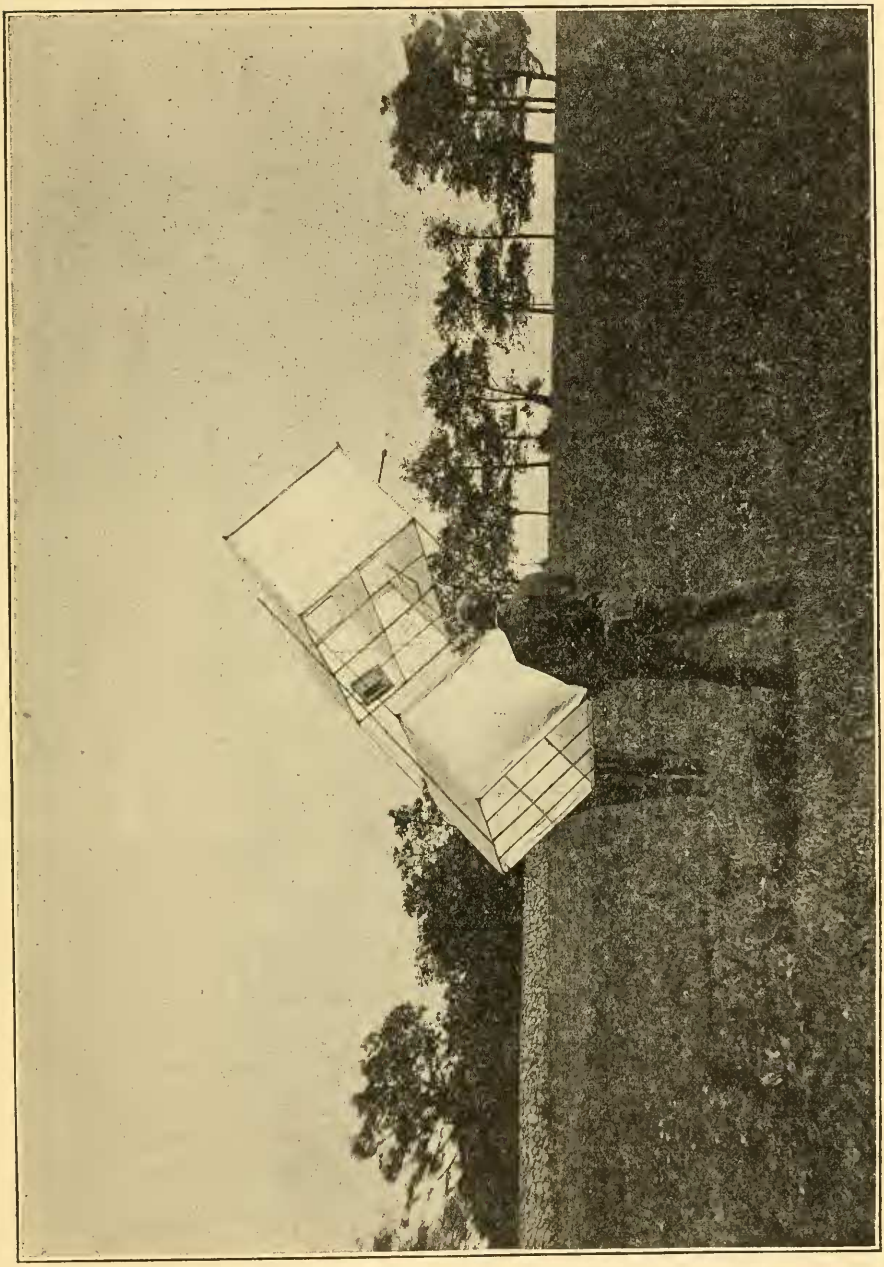


Fig. 4. Kite and instrument.

in making a flight. They carried a line 12,100 meters long. In our highest flight above referred to 11,735 meters of line was put out on nine kites.

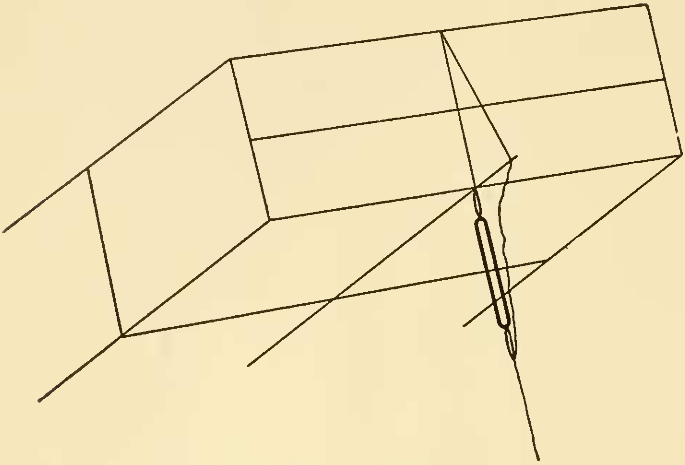


FIG. 5. Method of bridling kite.

The line is of piano wire made up about as follows:

Meters.	Inch in Diameter.
500	.026
500	.028
2,000	.032
3,000	.036
5,000	.040
5,000	.044

In all about ten miles of wire.

The reel is a very important part of the kite-flying apparatus. Its design should be such that the operator can easily control the rate at which wire goes out or comes in from 0 up to 4.5 meters per second. This enables him to keep his kites flying even if they are becalmed during flight, to throw them up through the calm strata of air which are often encountered, especially in the summer months, and, with the aid of a skilled field man, to start and land kites with little or no breakage. Our reel at Mt. Weather is equipped with a variable speed motor so geared to the drum that the wire may be brought in at any rate up to 2.7 meters per second.

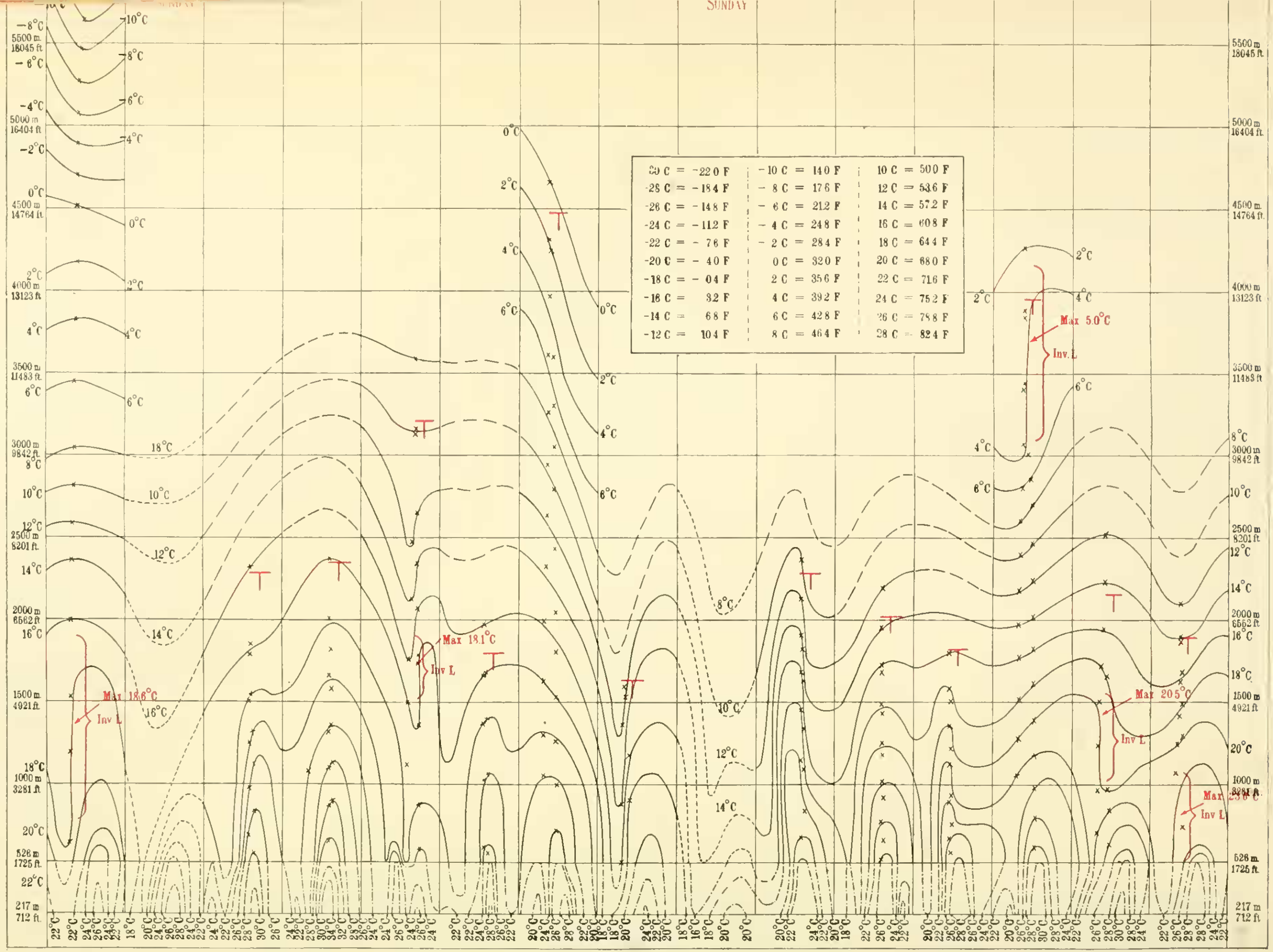


Fig. 6. Isothermal chart for August 1 to 15, 1908.

Too careful attention cannot be given to the condition of the reel preparatory to making a flight, and in general all apparatus must be well looked to. Failure in any one of the many details to be attended to at this time and during the flight is almost certain to result in some catastrophe. The field work has, for this reason, all the interest of our best college games and the man who is not equipped physically and mentally to enjoy such games will hardly enjoy or make a success of flying kites and balloons. The fact that for the past eighteen months no day (Sundays excepted) has passed in which one or more records of upper air conditions above Mt. Weather were not obtained speaks well for the spirit and efficiency of the men engaged in this work at that observatory.

The power plant at present in use is equipped with a 35 H.P. double cylinder gasoline engine, a 25 KW. dynamo, and an electrolyzer by means of which water is separated into oxygen and hydrogen, the latter for use in the captive balloons, and a gas compressor which may be used to compress hydrogen for shipment or to make liquid air with which to get sufficiently low temperatures to test sounding balloon instruments. A new combination steam power and heating plant is in process of building.

The computation of altitudes from the pressure trace of the meteorograph record by Laplace's formula and the evaluation of the other elements at these altitudes is another matter altogether and yet not devoid of interest. From five or six up to twenty or twenty-five levels are computed in each trace, *i. e.*, enough to show all peculiarities or changes in the temperature gradient or air currents, altitudes of clouds passed through, depth of cloud and fog layers and the highest points reached. From these data the temperature gradient, *i. e.*, the change of temperature with altitude, usually expressed in degrees centigrade per 100 meters, is plotted for each day and the upper air isotherms continuously charted. The whole, with more or less comment, is published quarterly in the Bulletin of the Mt. Weather Observatory. A study which has for its purpose the summarizing of the first year's data is still in progress. Valley stations are maintained on either side of the mountain. At these, data are collected for comparison with the surface readings obtained on Mt. Weather, 1,000 feet above them.

Five men besides the writer are engaged in the work of obtaining and reducing the records and in studying the resulting data. Duties are so arranged that these men take turns at outdoor as well as indoor work. In this way the work itself furnishes most of the physical recreation needed. None of the routine duties becomes especially irksome and the special lines of work are kept in better relation to each other and to the work as a whole than would be possible under another arrangement.

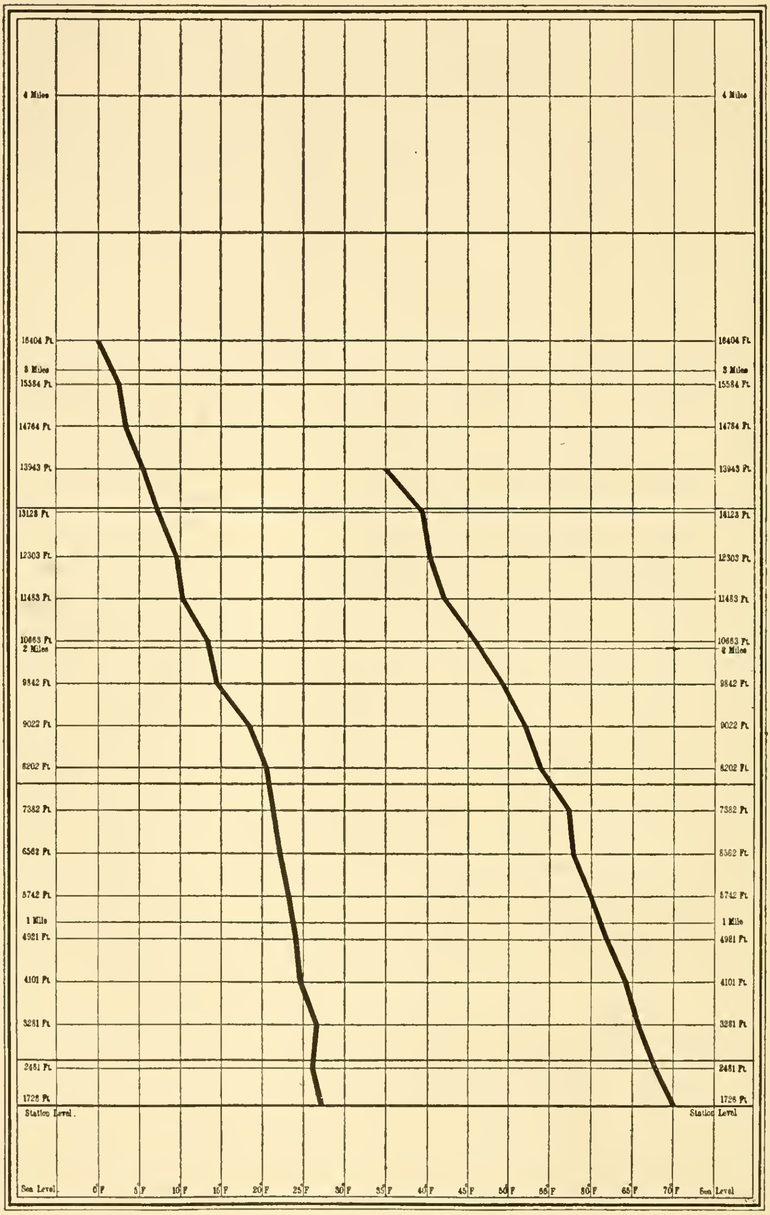
Concerning Data and Results.

The history of upper air work is, as we have seen, a brief one. The Hargrave kite and the sounding balloon are but fifteen years old, and with them began the study of the upper air as it is now carried on. This sort of investigation is comparatively new. The facts already—shall we say "aired"—have been made the subject of considerable comment. They themselves have so far had but little to say. They are cold and, among themselves, somewhat unsociable facts as yet, but we have become well enough acquainted with them to be certain that they with others yet to be "aired" or "unearthed" constitute a law-abiding community. "Unearthed" is used advisedly, for the energy liberated by the uranium deposits near the earth's surface may prove to be a considerable factor in the origin and development of disturbances occurring in the lower strata of the atmosphere. As a source of the energy displayed in the storms that continually pass over us, this factor has been considered by meteorologists as negligible compared with the energy received from the sun. The heating of the air from this latter source is due to the absorption by it of: (1) The direct rays of the sun, (2) the sun's rays which have been reflected from the earth's surface, and (3) the long heat waves radiated by the earth on account of its being heated by its absorption of the direct rays of the sun. Heat waves sent out by the earth due to other causes, such as radio-active minerals, would be operative in this third subdivision.

Water vapor absorbs the long heat waves readily and upon its vertical distribution in the atmosphere depends to a great extent the altitude at which their energy becomes effective in heating the air and setting it in motion. Observations upon this distribution show that at 2,500 meters the moisture content of the air is one third what it is at sea level, at 5,000 meters one tenth. Most clouds of the cumulus and stratus types form below the latter level. It is to be expected, therefore, and we are not disappointed in finding, that this lower stratum of air is in continuous and complicated motion, vertical currents as well as horizontal obtaining. Above this stratum the air movement seems to be less complex.

When an air mass is heated to a temperature higher than that of the air about it, as we now see may be the case near the earth's surface, an unstable condition obtains and convection currents set in. A body of air rising to higher levels is cooled by its own expansion as it passes into the rarer atmosphere. This is called adiabatic cooling. If the body of air in question were dry, the rate of adiabatic cooling would be about one degree Centigrade per 100 meters, or one degree Fahrenheit per 180 feet. If it contain moisture, it will not cool so rapidly for the moisture in condensing gives off its latent heat into the air. This effect is a function of the relative humidity and tends to accelerate the upward motion and postpone the return of stable conditions. Sufficient condensation soon takes place, so that heat from this source ceases to offset the adiabatic cooling, and the convection current finds its upper limit. Other moist air coming in from below supports the system thus set up, and the whole moves with the upper westerly wind. This sort of circulation on a larger or smaller scale, more or less modified by other circulations of the same sort, is in progress continuously. An almost unmodified type of it may often be observed during the summer months in the formation of a single cumulus cloud. The cloud formation shows the outlines of the ascending air column. The horizontal air movement is slight at such times and the column nearly vertical.

We should expect to find then that the change of temperature with altitude is less in the lower moist stratum of the atmosphere than in that immediately above it and always, when mean conditions for a sufficiently long time, say a year, are considered, less than the adiabatic rate of cooling for dry air, some moisture being present at all altitudes. The sounding balloon observations in middle Europe,



MEAN TEMPERATURES AT DIFFERENT ELEVATIONS ABOVE MOUNT WEATHER, JANUARY AND JULY, 1908.

FIG. 7. Mean gradients for January and July, 1908.

as compiled by Hann, give the mean gradient up to 3,000 meters as .45 degree Centigrade per 100 meters, while at twice this altitude the temperature change is .70 degree Centigrade per 100 meters.

Within the moist stratum itself, observations on the relative humidity show that the yearly minimum at the earth's surface occurs in the summer months. The result is that condensation begins at higher levels in summer than in winter. The temperature gradient responds to these conditions, being greater nearer the earth's surface and less near the upper region of the moist stratum in summer than in winter. Values closely approximating the adiabatic rate are often found for the first 500 meters above sea level in the summer months. Comparison of the mean temperature gradients as observed in Europe and in this country, at Mt. Weather and Blue Hill, points to the fact that condensation takes place at lower levels in western Europe than here. This is reasonable when the comparatively dry surface conditons which obtain on our continent are taken into consideration.

It follows from the above that the moist or storm stratum is: (1) Deeper in summer than in winter, (2) deeper over a continent than over the ocean or smaller land areas. Convection currents are more sluggish where the relative humidity at the surface is low and therefore the barometric changes are less pronounced: (1) In summer than in winter, (2) in continental than in insular climatic conditions. Upon these considerations alone we should expect the deeper storms to be the less intense, but this is not in general true and another factor, viz., the velocity of the upper westerly winds, must be taken into consideration. By storm intensity is meant the suddenness of the changes brought about by the passage of the storm—probably best measured by the barometric changes.

These upper currents apparently control the rate of motion of the storms. Their velocities are found to vary with altitude, increasing up to heights of 10,000 or 12,000 meters. They also vary with the seasons. At an altitude of 3,000 to 5,000 meters their mean velocity for January is found to be fully one and a half times the mean for July. It follows that, for a given season, the deeper storms move faster, *i. e.*, continental and insular climatic conditions

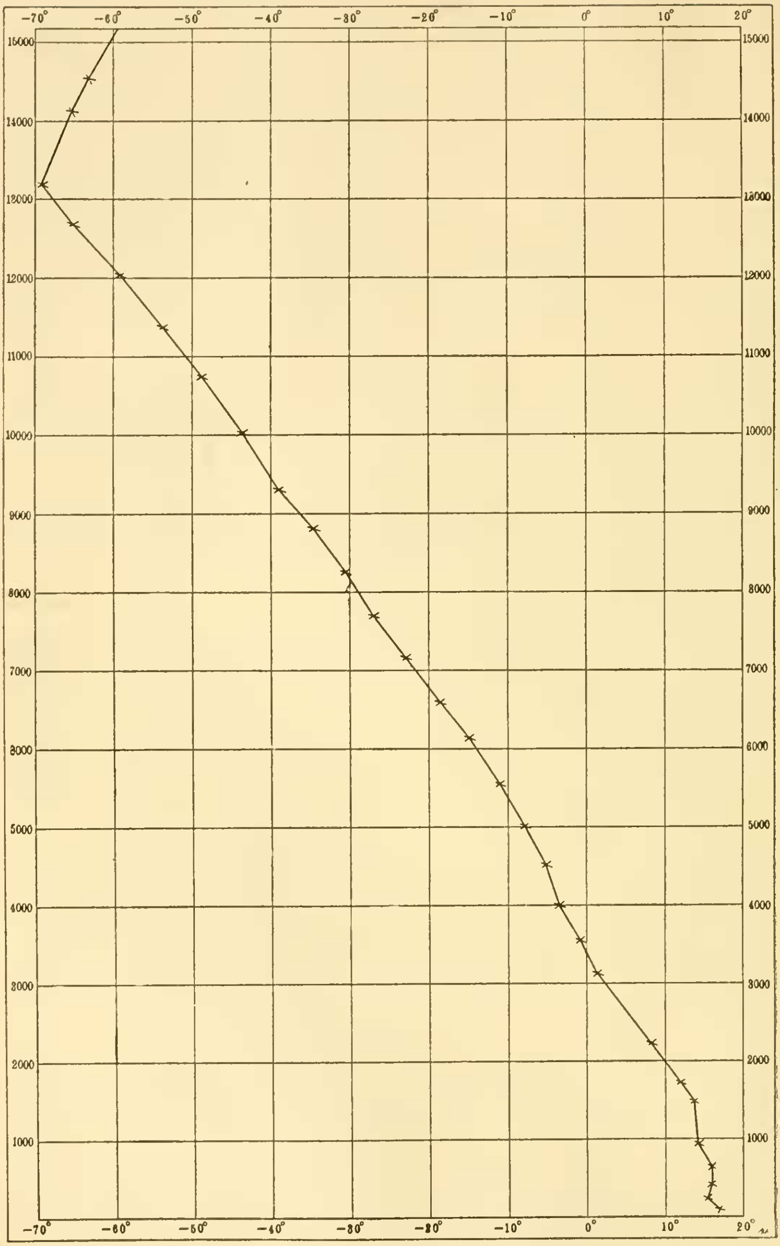


FIG. 8. Temperature gradient showing permanent inversion.

are respectively characterized by more and less rapidly moving storms. The effect of rapid motion upon a storm should be in general to intensify it, for, the more rapidly it moves, the greater the quantity of moist surface air that will be drawn up into it, and consequently the greater the amount of latent heat liberated because of the moisture condensation.

The conclusion is that, for a given location and season, the depth of a storm should indicate something of its rate of movement and consequently of its intensity. This is in accord with the experience at Mt. Weather.

It is said that American storms are more intense than those of Europe. If this be true, it is directly because of their more rapid motion and indirectly because of their greater depth.

Summer storms are less intense than those of winter. They are not only deeper but move less rapidly.

Cyclonic storm paths are, in general, found to pass through the regions of greater surface humidity. They seldom cross the arid or dry mountain regions, but travel along the great river basins, over the Great Lakes or along the gulf and ocean coasts.

So far the mean temperature change with altitude has been considered in two strata of the atmosphere: the lower, moist or storm stratum extending from sea level up to 4,000 or 5,000 meters, and the stratum above extending thence to 10,000 or 12,000 meters above sea level. In the first the mean temperature gradient is about .5 degree Centigrade per 100 meters, in the second about .7 degree Centigrade per 100 meters. The mean temperature at the top of the first stratum is about —10 degrees Centigrade, at the top of the second about —65 degrees Centigrade.

Above these strata still a third distinct stratum has been explored to an altitude of 25,000 meters above sea level. The striking peculiarity of this stratum is that in it the temperature increases from its base upward as far as it has been sounded. Its temperature gradient is small but negative. It was at first called the isothermal layer because the temperature seemed to change but little with altitude. Later observations, however, show a decided negative gradient or inversion of temperature and in consequence it is often called the upper or permanent inversion, the adjective being necessary to distinguish it from temporary inversions frequently found in the lowest of the three strata described. The existence of the permanent inversion is a well established and interesting fact. Of the many balloons sent into it, only a few have been followed all the way up with the theodolite, consequently the wind velocities have been but little observed. The winds are found to be variable and of low velocity, 3.5 meters per second has been observed. This is in pronounced contrast to the prevailing west winds of extremely high velocity which characterize the layer just below it. Leading meteorologists still differ as to the explanation of this warm stratum. Their opinions may be found in the October 1, 1908, number of *Nature* in the form of a report of the discussion organized on this subject by the committee of Section A of the British Association.

Isothermal charts, such as the one for the first two weeks in August, 1908 (Fig. 6), illustrate the change in the upper air temperatures with the time. The daily rise and fall of temperature is seen to extend to about 1,500 meters above the surface. Superposed upon this and somewhat complicated by it is an aperiodic change which follows the passage of high and low barometer over the station. This sort of change extends up to the permanent inversion. Still a third change in temperatures aloft with time has an annual period. The time of greatest cold occurs near the earth's surface in January, at an altitude of 5,000 to 7,000 meters it comes in March and April, 7,000 to 9,000 meters in July, and 9,000 to 11,000 meters in September.

Means of temperature records from 581 balloon ascensions made by Teisserenc de Bort show that the greatest annual fluctuation in temperature occurs at an altitude of 6,000 meters above sea level, *i. e.*, about the base of the second stratum above mentioned. From this level up the annual fluctuation decreases gradually. Almost as great a change occurs at the base of the lower stratum, *i. e.*, near the earth's surface. In this layer the fluctuation reaches a minimum at an altitude of 3,000 meters. These facts compel us to set aside the idea not long ago prevalent that, at an altitude 7,000 to 9,000 meters above sea level, the temperature should be constant throughout the year.

Special interest attaches to the particular study of the peculiari-

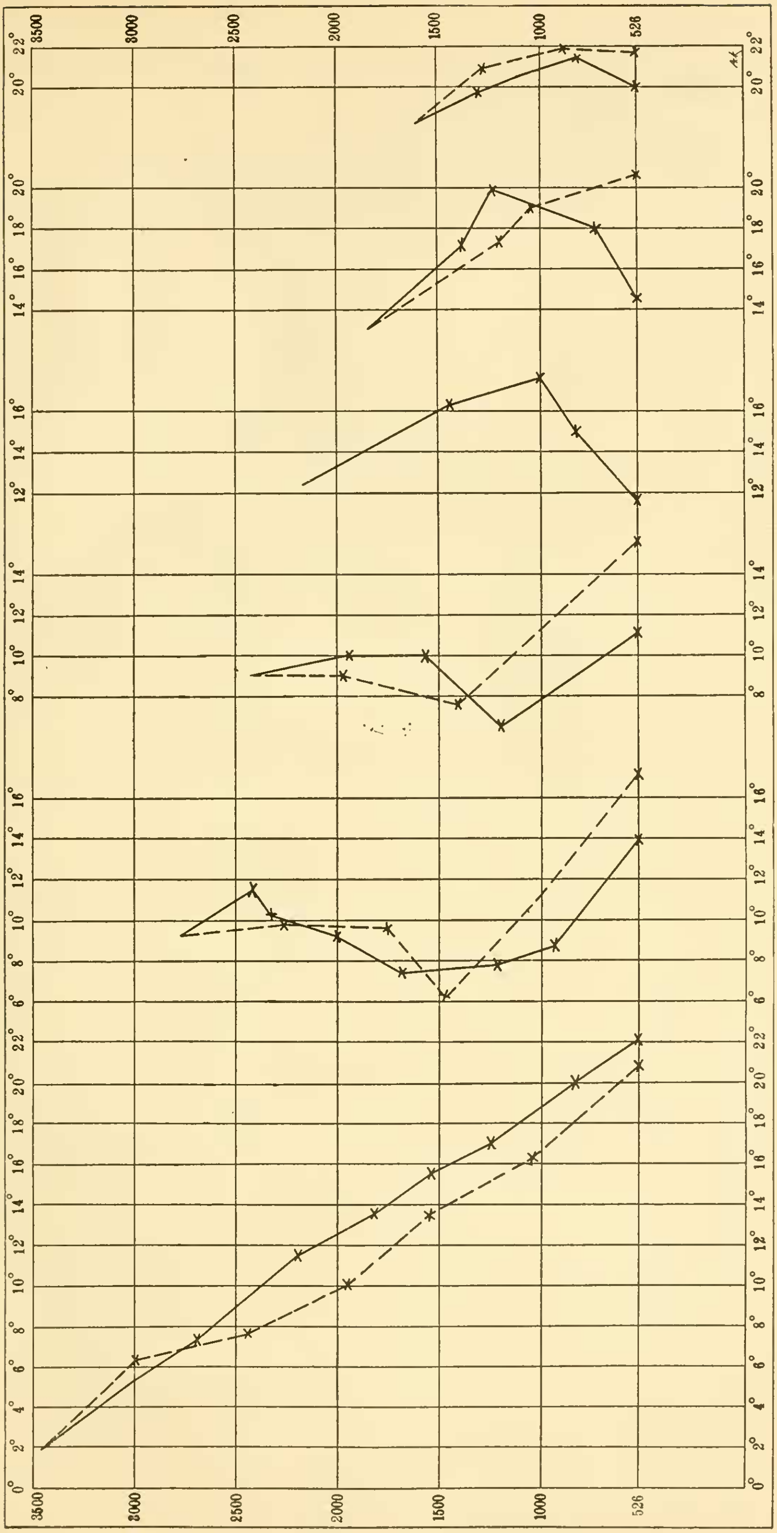


FIG. 9. The temperature inversion of September 15 to 19, 1908.

ties in the temperature gradient as recorded from day to day in the lower stratum, since these, together with the wind directions and velocities, must be relied upon for a knowledge of the air circulation in particular storms as they pass. Among the most interesting of these peculiarities are the inversions. Fig. 9 shows a characteristic series beginning on September 15, 1908, and ending September 19, 1908. The advent of this inversion is preceded by a small temperature change with altitude at 2,900 meters on September 14.

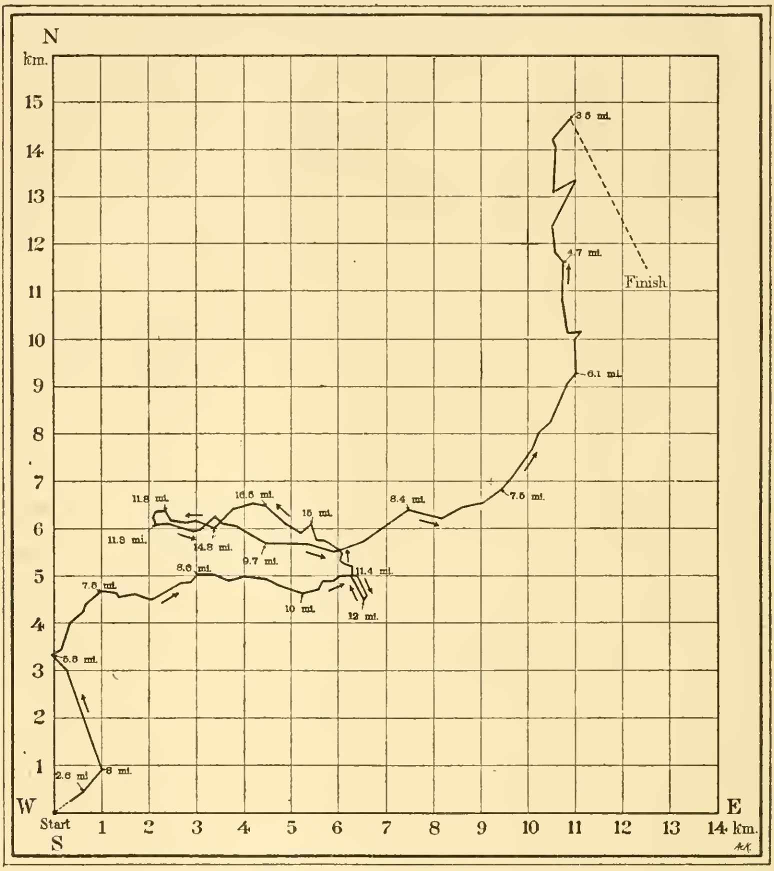


FIG. 10. Horizontal projection of path of a sounding balloon, Uccle, Belgium, July 25, 1907.

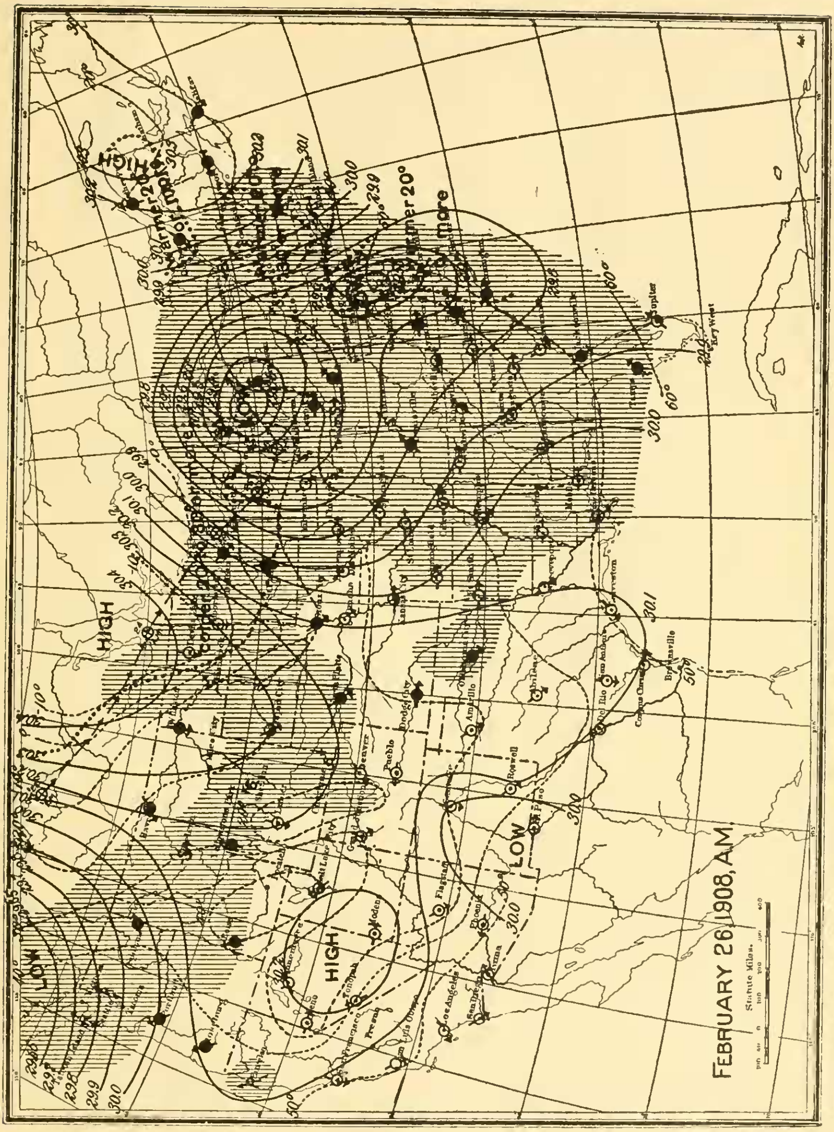


Fig. 11. Weather map of February 26, 1908.